WRAPPED MULTILAYER INSULATION FOR CRYOGENIC PIPING

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ABSTRACT

Many cryogenic systems require thermal insulation on piping and tubing containing cryogenic fluids. The lowest heat leak is typically achieved with conventional multilayer insulation (MLI) wrapped around the tubing and contained in a vacuum. However, because of inherent insulation compression and its effect on conventional netting spacer MLI, MLI performance on piping and tubing is four to ten times worse than MLI on a cryogenic tank or flat surface. Wrapped Multilayer Insulation (WMLI) is a high performance multilayer insulation designed for cryogenic piping that uses an innovative discrete spacer technology to control layer spacing/density and reduce heat leak. This paper reports on the initial development of WMLI and its demonstration as a feasible technology. The WMLI design was estimated in thermal models to provide four times better thermal insulation than conventional MLI on cryogenic piping. A WMLI prototype was built and had a measured heat leak 37% of the heat leak of conventional MLI insulating tubing. Test results for WMLI are presented, and plans for continued development of this insulation are discussed.

KEYWORDS: Multilayer insulation, cryogenic, thermal insulation

INTRODUCTION

Comparison to the state of the art

Next generation NASA vehicles (Heavy Lift Launch Vehicle and orbiting fuel depots) need improved cryogenic propellant transfer and storage for long duration missions.

Current cryogen feed line Multi-Layer Insulation performance has typically 10 times higher heat leak than tank MLI insulation. In cryogenic space craft propulsion systems, piping heat leak can be 50 – 80% of the tank heat leak. During each shuttle launch 40 – 50% of LH_2 is lost, about 150,000 gallons of LH_2, due to piping transfer, chill down and ground hold [1]. Cryogenic propellant lines are difficult to insulate with limited clearance and difficulty in out gassing and venting down to vacuum.

WMLI is an insulation system with engineered layer spacing, in which layer density and inter-layer heat leak are controlled via low contact area, low thermal conduction spacers. WMLI has a number of applications throughout government, national security and commercial sectors. Vacuum insulated pipe has a fairly broad market in industry and use, and WMLI may be a superior solution to current available technologies.

NASA Applications

- Cryogenic propellant piping insulation for NASA vehicles, including cryogenic landers, cryogenic upper stage launch vehicles and orbiting fuel depots
- Cryogenic piping insulation for Ground Support Equipment for launch facilities, launch vehicles, cryogenic upper stages and LH_2 fueled aircraft

Non-NASA Commercial Applications

- Ground Support Equipment for commercial launch facilities and cryogenic upper stage launch vehicles such as Atlas Centaur and Delta Cryogenic Secondary Stage.
- Cryogenic fluid handling piping such as Vacuum Insulated Pipe. Insulated cryogenic hoses for cryogen transfers to/from cryogenic dewars and tanks for research, medical and industrial uses.
- LN_2 handling applications for food and beverage industries for inerting and pressurizing.
- LNG industrial insulated transfer pipes.
- Spiral wrapped insulation for commercial dewars

DISCRETE SPACER TECHNOLOGY

Through a number of NASA contracts, Quest Product Development Corp and Ball Aerospace and Technologies Corp have developed an innovative approach to a more robust, higher performing and more predictable Multi Layer Insulation. The concept is the replacement of the traditional netting between radiation barriers with a discrete, proprietary, low thermal conductance micromolded polymer spacer. The basic technology, called Integrated MLI (IMLI), has demonstrated a significant reduction in heat leak over some of the highest performing conventional MLI. The Cryogenic Test Laboratory at Kennedy Space Center has performed independent testing using liquid nitrogen calorimetry to characterize the performance of IMLI. A 20-layer blanket had a measured performance of 0.41 W/m^2 (0.0069 mW/m-K) which is approximately 40% lower heat leak per layer than typical netting spacer MLI [2].

FIGURE 1. WMLI wrap concept

FIGURE 2. WMLI spacer concept

The spacers allow precise layer spacing and controlled layer density not affected by gravity, fabrication techniques or installation workmanship. The unique micromolded fabrication method of the polymer spacer allow a small cross sectional area to length ratio (1.1×10^{-6} m) to greatly reduce layer to layer conducted heat leak. Patents have been filed for the discrete spacer technologies. A number of derivative insulation products are being developed based on the discrete spacer technology.

Wrapped MLI (WMLI) is a derivative product based on the discrete spacer technology. WMLI is a high performance multilayer insulation designed for cryogenic piping that uses discrete spacers to control layer spacing/density and reduce heat leak. In a Phase I SBIR program, a WMLI prototype had a measured heat leak nearly four times lower than spiral-wrapped conventional MLI on cryogenic piping, and 25% lower heat leak than the higher performing "clamshell" (parallel MLI layup method). WMLI could provide advanced cryogen transfer line insulation and be the basis of a superior vacuum insulated pipe (VIP) technology.

Spiral wrapped conventional MLI performance is highly dependent on compression during installation. If the wrap is wound too tightly, the interface conductance through the netting increases producing higher heat leak. The reliance on installation workmanship makes it difficult to predict the heat leak through the cryogenic piping system. An advantage of discrete spacer technology is controlled, predictable layer spacing not affected by compressibility. The layer spacers eliminate interlayer touching, thus forcing the conducted heat leak through the low conductance spacers, which have a lower contact area between layers than a netting spacer. By reducing the conductance through the spacer, lower heat leak is obtained. A newer development for conventional MLI is a clamshell wrap layup method that attempts to reduce heat leak from the compression of a spiral wrap. WMLI prototypes were modeled and tested against spiral wrapped and clamshell MLI.

WRAPPED MLI PERFORMANCE

In a NASA Phase I contract, Wrapped MultiLayer Insulation (WMLI) prototypes were designed, fabricated, installed on 0.75" diameter piping and tested. The short duration and limited budget of a Phase I program required us to evaluate possible solutions for application of our discrete spacer technology with readily available materials. The lowest thermal conductivity material was silica glass beads. This was the material of choice for the Phase I activities, knowing that future improvements could be made via a custom polymer spacer. Modeling WMLI spacers estimated that the thermal contact area of traditional MLI netting is 15 times greater than the contact area of the WMLI spacers. The large netting contact area gives conventional MLI performance a large heat leak variation with wrap compression. WMLI has a fixed density and spacing, see Figure 3.

State of the art MLI cryogenic pipe insulation uses a 'clam-shell' approach and wraps each layer or quilt individually around the pipe to be insulated, and have achieved an effective emissivity of 0.023 for five layers. In the case of a WMLI spherical spacer, contact resistance can be controlled through the diameter of the spacer and the contact area of the spherical spacer with the radiation barrier. Using solid glass beads, the thermal model estimates heat leak as low as 1.6 W/m^2 for 1mm (0.040") diameter spacers could be obtained.

TEST RESULTS

A small, 10L, test tank and tube set was designed and fabricated for Phase I testing using liquid nitrogen boiloff calorimetry. Heat leak through the test tank was measured, then subtracted from total heat leak into the entire system (tank plus piping) to measure heat leak through the tubing. and evaluate different methods of insulation.

Heat leak measurements were made for three different multi layer insulation (MLI) layups on tubing:

1) WMLI wrapped five-layer blanket fabricated with 1 mil Dual Aluminized Mylar (DAM) with glass spherical spacers. The glass beads were 2.0 mm diameter, and are bonded to the mylar on a 1.59 cm grid pattern.

2) Spiral wrapped netting five layer MLI blanket, composed of 0.25 mil DAM two inches wide, wound in a spiral around the tubing with a 50% overlap, which results in 10 layers total

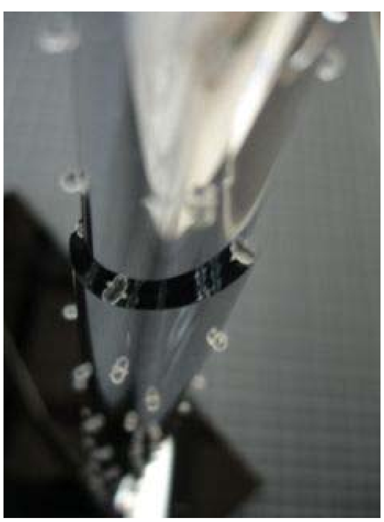

FIGURE 3. WMLI prototype

FIGURE 4. Test apparatus with tank and tube set.

3) Clamshell netting MLI five layer blanket, composed of 0.25 mil DAM with netting spacer, clamshell wrapped around tubing with a taped seam, which is a five layer blanket

The test results are shown above in this direct head to head measurement and comparison of Wrapped MLI versus spiral wrapped and clamshell MLI. Cold temperature was 76°K, hot side 294°K, tank only heat leak was 0.72W, tubing surface area was $0.1017 m^2$, relative standard deviation of measurements was about 3%. WMLI demonstrated a heat leak 27% of the heat leak of traditional spiral wrap MLI, and 74% that of the current state of the art clamshell MLI.

The correlations developed by Lockheed [3] have been used for many years to predict thermal performance of MLI, usually with an installation factor of approximately 2 to match actual performance on cryogenic tanks. While it may be generally understood that MLI wrapped around piping has higher heat leak than tank MLI, this data shows the Lockheed installation factor for spiral wrapped MLI is 22, for clamshell layered MLI is 8, and for WMLI prototypes is 5.8.

Modeling indicates the heat leak of WMLI with custom spacers could be 10 times lower than spiral wrapped MLI, and 46% better than the performance of the best tubing MLI installations. This advantage could be used to reduce the number of layers, reduce cost or reduce heat leak. Reduced number of layers would result in reduced mass and reduced cost. Modeling indicates WMLI could be further developed with custom spacers to obtain 3-fold lower heat leak from the Phase I results. This will be the goal of the Phase II program.

A Phase II NASA program is underway and it is expected that substantial improvements in thermal performance will be obtained. The program will develop custom spacers to reduce thermal, further develop manufacturing and assembly techniques, and produce a custom solution for vacuum insulated pipe. Historically, Quest R&D Phase II efforts have yielded an average 55% improvement over initial prototype thermal performance. Phase II work will optimize the spacer and wrap geometries through several generations of design, build and test cycles. In Phase II, custom spacers will be designed and tooled, which could reduce thermal conductivity of the spacer by seven fold. Furthermore, with a custom spacer, features can be designed to further minimize solid heat conduction through the part.

Table 1: Wrapped MLI Test Results

Test Article	*Effective Layers*	*Heat Leak, W*	*Heat Leak, W/m^2*	*Effective Emissivity*	*Conductivity mW/m*K*
WMLI	5	0.75	7.34	0.017	0.024
Spiral MLI	10	1.36	13.3	0.032	0.050
Clamshell MLI	5	1.00	9.82	0.023	0.017

FIGURE 5. WMLI prototype layer 4 installed around bends in tubing.

CONCLUSIONS

WMLI technology was successfully demonstrated feasible and moved to TRL4 with tests of a prototype component. A WMLI prototype had a measured heat leak of 7.3 W/m^2, which is four times lower heat leak than spiral wrapped conventional MLI on piping. WMLI has been shown to be a robust, repeatable insulation system with precisely controlled layer spacing, low contact resistance, low thermally conductive discrete spacers.

MLI wrapped on cryogenic piping was shown to have substantially higher heat leak than typical MLI installations. Thermal modeling and WMLI prototype measurements show WMLI has lower heat leak than spiral wrapped MLI on tubing.

Quest Product Development Corp and Ball Aerospace have developed a number of next generation MLI solutions based on proprietary discrete spacer technologies. WMLI R&D is continuing with a NASA Phase II contract, and further improvements in thermal performance are being pursued. WMLI could provide improved cryogen transfer lines and Vacuum Insulated Pipe, and lower loss cryogen fluid transfers as Ground Support Equipment for cryogenic fueled launch vehicles and aircraft.

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